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Life cycle cost analysis of fuel cell based cogeneration system for residential application in Malaysia

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ABSTRACT

Fuel cell is an environmental friendly cogeneration system with the capability of producing electricity and thermal energy. Thermal energy emitted during the production of electricity can be used to meet the heating loads. The purpose of this study is to analyse the feasibility of the fuel cell based system to be used in Malaysia. The cost effectiveness of using cogeneration system was compared to the conventional grid energy system. Two models of grid-independent and cogeneration system are developed and simulated using HOMER® software to determine the energy required meeting the hourly average electric and thermal loads of the residence. These two models were simulated with and without battery pack options to optimize the utilization of electricity generated by the fuel cell system. The results include a comparison between the energy used in cogeneration systems and the conventional residential energy system. Comparisons of the life cycle cost and the payback period of the cogeneration system to the conventional residential energy systems were also presented. The results indicate that cogeneration systems can reduce the primary energy use by 30–40%.

Contents

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1. Introduction

Electricity is a necessity in our daily life as it provides power for lighting, electrical appliances, space conditioning, and water heating. In Malaysia, the residential energy use accounts for more than 14,365 GWh or 19% of total electricity used in Peninsular Malaysia in year 2006 [1]. The electricity for most residential buildings is supplied from the conventional power generation plants over the nationwide electricity grid. The thermal efficiency of the conventional power generation is usually less than 40% [2]. Besides that, the waste heat generated at the utility plant cannot be used effectively.

The annual increase in residential projects necessitates the effort to look for an alternative ways to provide efficient and clean power. One of these is fuel cell, which have been used for more than a decade in this country. Ministry of Science, Technology and Innovation (MOSTI) has been funding the Malaysia National Fuel Cell Research and Development Programme from year 1996 to 2007 with total amount of MYR34 million (USD 1 = MYR 3.5) and the hydrogen production and storage technologies with MYR7 million from year 2002 to 2007 but they are mainly focused on transportation sector [3].

Most of the western countries, such as the United States and members of the European Union have started implementing residential fuel cell system in their countries and the effect is positive and encouraging. In Asia, Japan has successfully implemented more than 50 unit residential fuel cell systems in year 2004 [4]. However, such has not been carried out in Malaysia and many other parts of the world.

It is expected that if fuel cell based energy system can be implemented in the future for residential area or commercial sector, the environmental quality will be improved. The objectives of this research are; to study the system performance and the feasibility of fuel cell system for residential application in Malaysia, and to develop a model to evaluate the characteristics of energy use, life cycle cost and payback period of the system.

Nomenclature

ACF	annual cash flows (MYR)
$C_{ann,tot}$	total annualized cost (MYR/year)
Cp	specific heat (kJ/kg K)
CRF	capital recovery factor
C_{rep}	replacement cost (MYR)
E	energy (kWh)
$\dot{E}$	electrical power (kW)
EP	energy price (MYR)
I	life of the equipment (year)
IC	initial cost for the system (MYR)
LCC	life cycle cost (MYR)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
MC	annual maintenance and operating cost (MYR)
MOSTI	Ministry of Science, Technology and Innovation
PB	payback period (year)
PEMFC	proton exchange membrane fuel cell
Q	heat transfer (kWh)
$\dot{Q}$	heat transfer rate (kW)
r	rate of return for a capital (%)
MYR	Malaysian Ringgit
R_{comp}	component lifetime (year)
R_{proj}	project lifetime (year)
R_{rem}	remaining life of the component at the end of the project lifetime (year)
T	temperature (°C)
T	time (s)
TC	total cost (MYR)
TEU	total energy use (kWh)
V	volume (litres)
$\dot{V}$	volume flow rate (m^3/s)

Greek letter

ρ	density (kg/m^3)

Subscripts

avg	average
CW	cold water from water line
DW	domestic water
FC	fuel cell
HW	hot water
TS	thermal storage
XHW	other appliances except hot water

2. Conceptual design considerations and survey data

2.1. Conceptual design considerations

The design consists of a fuel cell system and vapour compression heat pump. A Fuel cell system can generate electricity and the waste heat produced can be recovered for space and domestic water heating. However, Malaysia is located in a hot and humid climate; therefore domestic space heating is not commonly used in this country. The thermal energy from the fuel cell system is then transferred to the thermal storage tank. The stored energy then can be used for domestic water heating. Hot water is generally used in a household for food preparation, bathing, dish washing, face and hand washing. In this research, the evaluation is based on the conceptual design shown in Fig. 1 [5].

For the reason mentioned above, the thermal energy generated from the fuel cell system is used for domestic water heating and

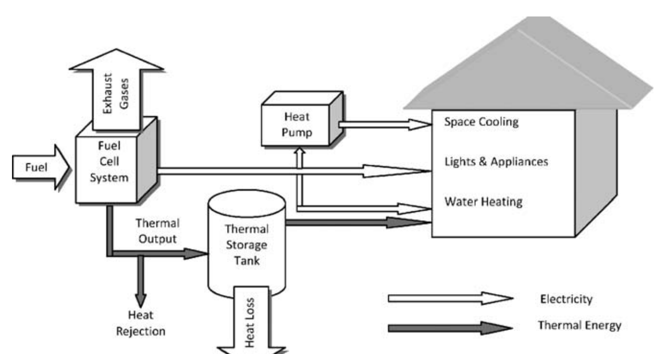

Fig. 1. Cogeneration system.

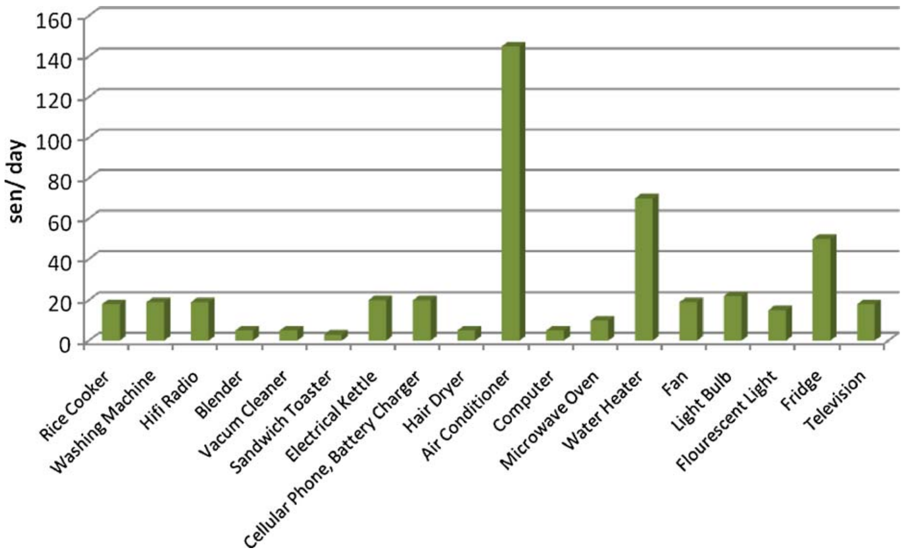

Fig. 2. Estimated daily electricity cost per day of various domestic appliances.

the generated electricity can be used to power appliances. Thermal storage tank could be added to the system for better storage of thermal energy.

2.2. Survey data

The household electricity consumption is very much dependent on the family size, living habits, age and number of electrical appliances and usage time. A study was carried out to estimate the average electricity consumption for three different categories of household. They are the low cost house with average spending of approximately MYR65 per month, medium cost house spending about MYR110 per month and for bungalow spending up to MYR350 per month. The cost of energy used by various appliances in Malaysia is shown in Fig. 2 [6].

Fig. 2 shows that water heating is the second largest cost per day after air conditioning. The usage of water heater is 14% of the total energy consumption per month in a typical urban house. The electricity consumption for a typical urban house is shown in Fig. 3 [7].

If the fuel cell is used in a house, the heat rejected can be utilized effectively and 14% of electricity consumption for water heater can be saved [7]. So, there is a potential replacement of conventional power supply in residential sector with fuel cell technology in the future as it can fulfil the demand by generating electricity and thermal energy. In addition, fuel cell can provide continuous and uninterrupted power supply. Therefore, the interruption of electricity supply will be greatly reduced in residential sector in the future if energy is supplied by fuel cell system.

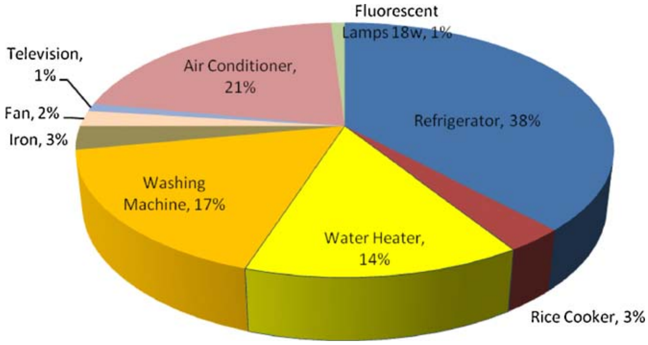

Fig. 3. Electricity consumption for a typical urban house [7].

3. Methodology

Studies on the application of photovoltaic for vapor compression air conditioning system found that the air conditioning demands and solar energy availability do not coincide for residential purpose due to the several reasons. First, the instantaneous cooling loads comprise of sensible heat gains which dependent on ambient temperature does not fluctuate similarly as radiation. Second, the actual cooling loads are delayed due to building storage characteristics and third, most residents are not at home in the daytime and hence, nighttime requires greater cooling demands [8].

The feasibility of using fuel cell for residential applications in Malaysia is discussed in this paper. The energy requirements for a residential building have been investigated and the following applications will be considered:

- Domestic water heating load
- Space cooling load
- Lightings and appliances

With the fuel cell system, thermal energy can be used for domestic water heating and the electric power generated can be used for the lighting, electrical appliances and space cooling purposes. Due to the space heating is not required in tropical countries; the entire thermal energy from the fuel cell can be utilized for domestic water heating.

3.1. Fuel cell system

Fuel cell requires several other sub-systems and components to form a complete fuel cell system to generate electricity and heat. The fuel cell systems greatly depend on the fuel cell type, fuel used and the application. Fuel cells are electrochemical devices that convert chemical energy into electrical energy directly when hydrogen fuel is combined with oxygen. Water is the only by-product and no pollutants are produced if pure hydrogen is used. Hydrogen reformer is needed to extract the hydrogen from the fuel if hydrocarbons source is used. Fuel cells are much more efficient than conventional energy sources because it converts chemical

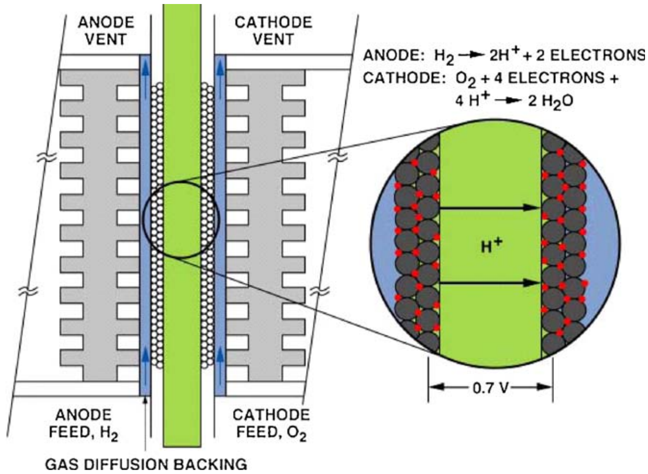

Fig. 4. Proton exchange membrane fuel cell [12].

energy of the fuel directly into electricity without going through an intermediate combustion step.

Among different types of fuel cells, Proton Exchange Membrane Fuel Cell (PEMFC) also called Polymer Electrolyte Fuel Cell is the most promising type for transportation and small-scale stationary power generation application due to its lower operating temperature and better load characteristics [9].

Presently, many companies have developed fuel cell systems for residential use. Plug Power Inc. recently developed a 7 kW PEMFC for a single family house not connected to the utility grid. Energy Partners Inc. recently announced the development of a 3 kW PEMFC for residential grid-connected application. Toyota Motor Corporation announced the home-use fuel cell cogeneration units as part of a government project to verify the practical use of CO_2 reducing stationary fuel cells [4]. Panasonic is in the process of developing a new fuel cell cogeneration system for home use and planned for mass production and commercialization by March 2010 [10]. Many fuel cells with capacities 5–10 kW have the capability to be operated either grid connected or off-grid. The details of the systems are considered proprietary, because the systems are still in development phase. The companies claim that their products will produce electricity competitive with current residential electricity rates and significant cost savings especially at countries where electricity is more expensive.

The PEMFC technology is one of the high efficiency devices which is able to generate high power supply and it consist of:

- The ion exchange membrane.
- An electrically conductive porous backing layer.
- An electro-catalyst (the electrodes) at the interface between the backing layer and the membrane.
- Cell interconnected and flow plates that deliver the fuel and oxidant to reactive sites via flow channels and electrically connected the cells as presented in Fig. 4.

Hydrogen and oxygen gases react to form the water, electricity and thermal energy in the fuel cell stack. The fuel cell system is illustrated in Fig. 5 [11]. The components of a PEMFC stack are the anode, the proton exchange membrane, the cathode and the gas channel for each electrode. Hydrogen extracted from the natural gas is supplied to the anode side of the stack. At the anode, hydrogen gas reacts to form electrons and protons over noble metal catalysts. The protons diffuse through the membrane, while the electrons are transferred over an external circuit to the cathode side. At the cathode the protons and electrons react with the oxygen in the cathode stream to form water which is carried out of the stack in the cathode gas channel (product stream). The PEMFC operates usually within a range of 65–90 °C.

PEMFC stack to be used in the residential are consist, fuel reformer, fuel cell stack with appropriate water, air and thermal management subsystem, converter and power conditioner. Since hydrogen is not readily available in nature, a fuel reformer is required to produce the hydrogen stream gas from the natural gas or other hydrocarbon fuel. The detail operation of PEMFC systems describes in Ref. [12].

Energy requirements data for a residential building are established to analyse the proposed fuel cell based system. A schematic model is developed to simulate the response of the building thermal and electrical load. This analysis can evaluate the optimal combination of the fuel cell and other equipments to provide the most encouraging output from the proposed cogeneration system.

Software called HOMER from National Renewable Energy Laboratory (NREL) was used to simulate the system. The software can simplify the task of evaluating designs options for both off-grid and grid-connected power systems for remote, stand-alone and distributed generation applications. It also can be used to evaluate the economic and technical feasibility of a large number of technology options and to account for variation in technology costs and energy resource availability [13]. HOMER is used in this research to simulate the condition and to determine the fuel requirements based on the systems characteristics and the variation in the loads.

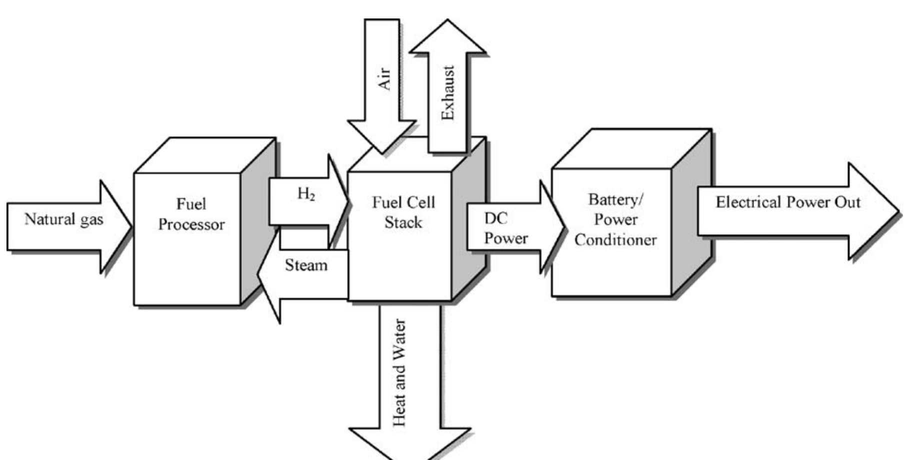

Fig. 5. Fuel cell system [11].

3.2. Survey data

This study carried out for a single family house as it is the most common living place in Malaysia. The number of occupants in a selected single house is assumed to be about 6 people. The percentage consumption for water heater and air conditioner are approximately 14% and 21% respectively out of the total electricity consumption [7]. The rest of the energy used is for lighting and appliances. These data will be used to get the monthly energy consumption for a typical household.

To analyse the proposed residential fuel cell based system, the percentage of electricity used for various type of appliances are necessary. A survey was conducted in the areas around Kuala Lumpur. Electricity consumption records were collected and combined to get the average electricity consumption for a typical household in Malaysia. Data collected based on the monthly bill of each residence and it was used for this entire simulation. The average monthly electricity consumption for a typical household in Kuala Lumpur is essential for this study.

3.2.1. Domestic hot water

Domestic hot water is considered as a largest thermal energy used in a house. The daily hot water consumption is given by Ref. [14]. According to ASHREA Handbook, the medium guideline represents the overall average of the hot water use for a typical residence. As a result, for a family with 6 occupants, the average monthly hot water use will be 20,520 l (20.52 m^3). Daily domestic hot water use profile is based on the survey data collected for every hour. However, the main factors in determining the energy use for water heating are the consumption profile, the design temperature of the hot water, the heater efficiency and the incoming water temperature. The design hot water temperature (T_{HW}) is assumed to be 60 °C (140 °F). The water temperature (T_{CW}) is dependent on the weather, air, water reservoir and ground temperatures. But for sufficiently long water pipes, the water temperature would be practically the same as the ground temperature at the depth of the pipes. As Malaysia is a tropical country, the incoming water temperature is assumed to be the same as average monthly ground temperature. The electric power to heat the domestic water from the T_{CW} to the desired hot water temperature T_{HW} is given by

$$\dot{E}_{DW} = \dot{m}_{HW} C_p (T_{HW} - T_{CW}) \tag{1}$$

$\dot{m}_{HW}$ is the mass flow rate of the incoming water and it is based on the data collected for the duration needed to accumulate a litre of water. The mass flow rate is assumed to be 0.035 m^3/s.

$$\dot{m} = \rho \dot{V} \tag{2}$$

The time needed to heat one litre of incoming water from 26 to 60 °C is 6 s, which was collected based on the experimental method. This experiment carried out by the time recorded for the incoming water to be heated and stabilized at 60 °C by a water heater. This data was used to determine the time needed to heat the required amount of water for a particular time. This will represent the amount of thermal energy needed from fuel cell to raise T_{CW} to T_{HW}.

3.2.2. Electric load for space cooling, lighting and appliances

Data for electricity used (excluding water heating) has been determined by total electricity consumption for the above representative household. The hourly energy used for the space cooling, lighting and appliances can be obtained by subtracting the energy used for water heating.

3.3. Cogeneration system model

Results from the model will be used to evaluate the feasibility of conversion from the conventional energy system to fuel cell based system. The model was developed for the fuel cell energy system to match the energy output of the system with the thermal and electric energy requirement in the residence throughout the year. This schematic diagram is developed and simulates using HOMER® software, life cycle cost and payback period has been calculated using the Microsoft Excel.

3.3.1. System description

The system can be divided into the following subsystems;

- Fuel cell
- Thermal storage tank
- Domestic water heater
- Battery pack

The fuel cell subsystem considered in this research is based on proton exchange membrane fuel cell (PEMFC). The subsystem is illustrated in Fig. 6.

In this study, natural gas is used as a fuel supply to the fuel cell. A fuel processor or a reformer is required to extract the hydrogen from the natural gas and react with the oxygen in the air to provide electricity and thermal energy. The natural gas is provided by Gas Malaysia and the tariff for natural gas and electricity are necessary for calculation.

3.3.1.1. Thermal storage tank. The thermal storage tank is used to store the thermal energy rejected from fuel cell during the process of electricity generation. The thermal energy is not required at all time; the peak season of thermal energy used is primarily on afternoon and evening for a typical family. The excessive thermal energy during the off peak hours can be stored and prepared for peak hours.

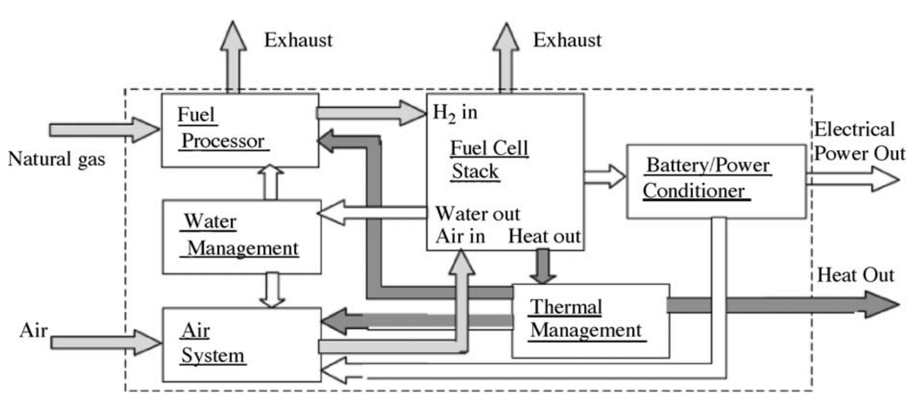

Fig. 6. Fuel cell subsystem diagram [12].

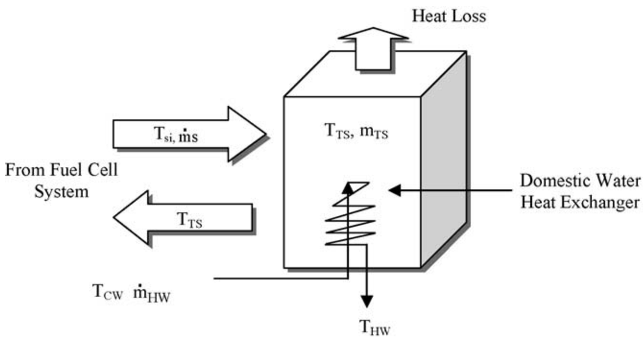

Fig. 7. Thermal storage tank and domestic water heating subsystem [5].

3.3.1.2. Domestic water heater. In this subsystem the heat is transferred through the heat exchanger from the tank to achieve desired hot water temperature. Certain amount of heat will be lost to the environment due to the temperature different between the storage tank and the surrounding. Thus the efficiency of the heat provided from the fuel cell to the tank and reach to the user must be taken into consideration. The efficiency is assumed to be 60%. The system is shown in Fig. 7.

Battery is an optional subsystem in this analysis. Two different combinations will be evaluated in order to get the optimal results. The first combination is the fuel cell system without the battery system and the second combination is with the battery system.

3.3.2. Operating regimes

The model is simulating the energy use during each hour for the whole year. The input data for the model based on HOMER software are as follow:

- The numbers of operating hours (from 1 to 8760).
- The electric load excluding the water heating for a day is assumed to be same for that particular month (kWh).
- The electric load due to water heating for a day is assumed to be same for that particular month (kWh).

The baseline of the average electricity consumption is 10.3 kWh/day. Thus, the scale annual average of the electricity load must meet the minimum baseline load to fulfil the requirement of the household. This is also applied to the thermal load requirement, which has a baseline load of the average consumption of 1.85 kWh/day. Therefore, 11 and 15 were used for the scale annual average of the electricity load and 3 and 5 for the thermal load in this study. The objective is to calculate the optimal combination of fuel cell and other components with the minimum cost for the fuel cell energy system over the conventional system. Few potential configurations are evaluated for each optimization variables. HOMER will configure and sort them by the net present cost. The optimal combination is selected for further evaluation.

3.4. Life cycle cost analysis

A life cycle cost analysis comparing the cogeneration system to conventional system is performed to evaluate the economic benefit of the cogeneration system. The life cycle cost of each system under consideration is calculated using the following equation:

$$LCC = IC + \sum_{i=1}^{I} \frac{TEU \times EP}{(1+r)^i} + \sum_{i=1}^{I} \frac{MC}{(1+r)^i} \tag{3}$$

The cost of the fuel cell system is considered to be US$1000/kW which is approximately MYR3500/kW (1US$ = MYR3.5). Replacement of the fuel cell stack is the main maintenance cost for every 40,000 h of operation. The operating and maintenance cost is MYR0.03/h.

3.5. Net present cost

Net present cost is to determine the feasibility of investment of a project. This method could be employed to identify the most essential of feasible combination in this study. The net present cost of an investment of a project is the different between the sum of the discounted cash flows which are expected from the investment and the amount which is initially invested.

Simulation results are based on the total net present cost of the system which is can be calculated by the following equation [13]:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(r, R_{proj})} \tag{4}$$

3.6. Salvage cost

The salvage value is the value remaining in a component of the system at the end of the project lifetime. It is assumes linear depreciation of components, meaning that the salvage value of a component is directly proportional to its remaining life. It also assumes that the salvage value is based on the replacement cost rather than the initial capital cost. This is expressed mathematically as [13]:

$$S = C_{rep} \frac{R_{rem}}{R_{comp}} \tag{5}$$

3.7. Payback period

The payback period is the time taken to gain a financial return equal to the original investment. A simple payback period can be calculated by the total cost of the system over the annual cash flows (annual total cost saving) and can be calculated by the following equation:

$$PB = \frac{TC}{ACF} \tag{6}$$

The payback period is a simple method of evaluating the viability or feasibility of the investment. In this study, the total cost of the project includes the initial cost of the setup and the replacement of the components where necessary. While the annual cash flow is the total cost saving of the energy use compare to the conventional energy consumption.

4. Results and discussions

4.1. Results of survey data

Table 1 and Fig. 8 indicate the survey data for the average monthly electricity consumption and water usage for a typical household in Kuala Lumpur. Table 2 shows the minimum hot water usage per person in a day and Fig. 9 shows the residential average hourly hot water use for the respective household.

Average monthly ground temperature in Malaysia is tabulated in Table 3 [15]. Based on Eq. (1), the average electricity needed to heat up the water to the design hot water temperature is shown in Table 4.

Tables 5 and 6, are the hourly energy needed to heat up the amount of water from T_{CW} to T_{HW} and the electricity used for other appliances except water heating for a typical family.

Parameters data and the optimization variables for the software simulation are tabulated in Tables 7 and 8, respectively. While the

Table 1
Average monthly electricity consumption for a typical household in Kuala Lumpur.

Month	Typical household											
	January	February	March	April	May	June	July	August	September	October	November	December
Monthly energy used (kWh/mth)	380	359	376	388	379	344	357	356	374	359	360	355
Water heater 14% (kWh/mth)	54	51	53	545	54	49	50	50	53	51	51	50
Air conditioner 21% (kWh/mth)	80	76	79	82	80	73	75	75	79	76	76	75
Light and appliances (kWh/mth)	247	234	245	253	247	224	23	232	244	234	234	231

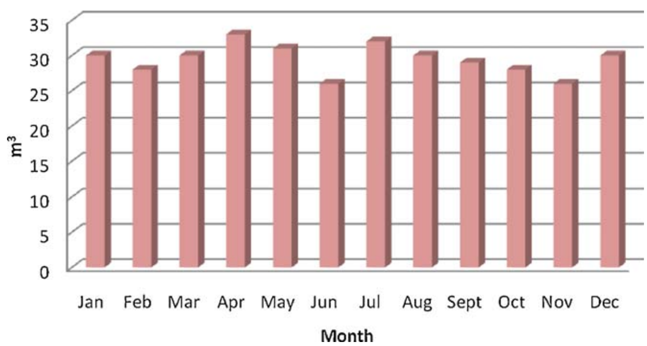

Fig. 8. Average monthly water use for a typical household in Kuala Lumpur.

Table 4
Monthly electric power needed.

Month	Electric power (kWh)
January	4.977
February	4.857
March	4.822
April	4.842
May	4.857
June	4.932
July	4.977
August	4.951
September	4.902
October	4.867
November	4.904
December	5.004

Table 2
Hot water demand and use guidelines (litres per person) [14].

Guideline	Maximum hourly	Peak 15 min	Maximum daily	Average daily
Low	11	4	76	53
Medium	19	7.5	18	114
High	34	11.5	340	204

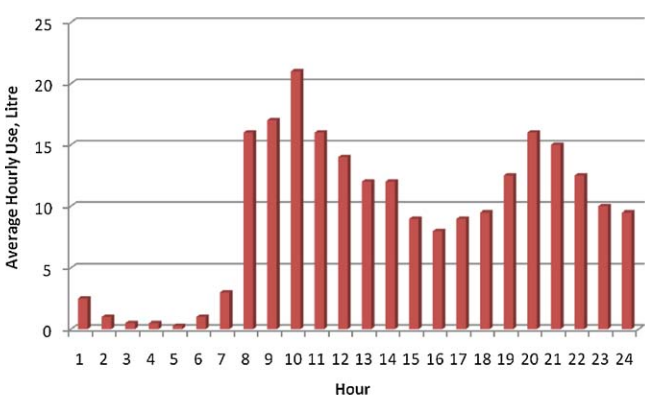

Fig. 9. Residential average hourly hot water use.

Table 3
Average monthly ground temperature in Malaysia.

Month	Ground temperature (°C)
January	26.1
February	27.0
March	27.2
April	27.1
May	27.0
June	26.5
July	26.1
August	26.3
September	26.7
October	26.9
November	26.6
December	26.0

equipment price and the energy prices are presented in Tables 9–11 [5,16,17].

4.2. Conventional systems

Based on the model established, a total of 4387 kWh per year is used for by typical household in Malaysia. From the electricity tariff shown in Table 11, a family has to pay approximately MYR 1200 per year. If a fuel cell cogeneration system is installed to replace the conventional system, the viability of the fuel cell energy system is calculated based on life cycle cost.

4.3. Cogeneration systems

4.3.1. Cogeneration system without battery option—scenario A

A schematic model was designed without the battery. Based on the typical household data and the parameters shown in Tables 7 and 8, a fuel cell and a converter of 1 kW are the optimal combination among the optimization variables. As fuel cell is a direct current component, a converter is required for the system. The above optimal combination is named as scenario A.

The baseline of typical family for electricity load and thermal load are 10.3 kWh/day and 1.85 kWh/day respectively. A new fuel cell energy system setup must meet the baseline demand and with the minimum net present cost. Four sensitivities are simulated and each of them with 36 combinations. The first potential combination (scenario A) is chosen, which can provide 11 kWh/day for electricity load and 2 kWh/day for thermal load with a total net present cost of MYR 22,995. This new fuel cell energy system cost which can be used for 20 years is tabulated in Table 12.

With the annual real interest rate of 5%, the cash flow diagram for Scenario A is shown in Fig. 10. The fuel cell system has to be replaced for every 5 years, as the lifetime of the fuel cell is only 40,000 h or approximately 5 years. The replacement cost must be considered as the fuel cell subsystem price is the major cost. The initial capital cost for the whole project is MYR 3700 with the consideration of annual interest rate and the total cost for the whole project would be MYR 22,995 for 22 years. Based on Eq. (5), the salvage cost of the project is MYR 818 at the end of the project lifetime.

Table 5
Hourly energy needed for water heating.

Month	January	February	March	April	May	June	July	August	September	October	November	December
Hour	Electricity consumption for water heating (kWh)											
1	0.021	10.0210	10.0210	10.0210	10.0210	0.021	0.021	0.021	10.0210	10.0210	10.0210	0.021
2	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
3	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
4	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
5	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
6	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
7	0.025	0.024	0.024	0.024	0.024	0.025	0.025	0.025	0.024	0.024	0.024	0.025
8	0.132	0.129	0.128	0.129	0.129	0.131	0.132	0.132	80.1320	80.1320	0.131	0.133
9	0.141	0.137	0.136	0.137	0.137	0.139	0.141	90.1410	0.139	0.138	0.139	0.141
10	0.174	0.170	0.168	0.169	0.170	0.172	0.174	0.173	0.171	0.170	0.171	0.175
11	0.132	0.129	0.128	0.129	0.129	0.131	0.132	0.132	0.1320	0.1320	0.131	0.133
12	0.116	0.113	0.112	0.113	0.113	0.115	0.116	0.115	0.114	0.113	0.114	0.117
13	0.099	0.097	0.096	0.097	0.097	0.098	0.099	0.099	0.098	0.097	0.098	0.100
14	0.099	0.097	0.096	0.097	0.097	0.098	0.099	0.099	0.098	0.097	0.098	0.100
15	0.075	0.073	0.072	0.072	0.073	0.074	0.075	0.074	0.073	0.073	0.073	0.075
16	0.066	0.065	0.064	0.064	0.065	0.066	0.066	0.066	0.065	0.065	0.065	0.067
17	0.075	0.073	0.072	0.072	0.073	0.074	0.075	0.074	0.073	0.073	0.073	0.075
18	0.079	0.077	0.076	0.077	0.077	0.078	0.079	0.078	0.077	0.077	0.077	0.079
19	0.103	0.1	0.1030	0.1	0.1	0.103	0.103	0.103	0.102	0.1	0.102	0.104
20	0.132	0.129	0.128	0.129	0.129	0.131	0.132	0.132	0.130	0.130	0.131	0.133
21	0.124	0.1240.1	0.1240	0.1240.1	0.1240.1	0.123	0.124	0.124	0.122	0.1240.1	0.122	0.125
22	0.103	0.1	0.1030	0.1	0.1	0.103	0.103	0.103	0.102	0.1	0.102	0.104
23	0.083	0.081	0.0830	0.081	0.081	0.082	0.083	0.082	0.082	0.081	0.082	0.083
24	0.079	0.077	0.076	0.077	0.077	0.078	0.079	0.078	0.077	0.077	0.077	0.079

Table 6
Hourly energy needed excluding water heating.

Month	January	February	March	April	May	June	July	August	September	October	November	December
Hour	Electricity consumption excluding water heating (kWh)											
1	0.507	0.478	0.502	0.519	0.506	0.47	0.475	0.4780.4	0.499	0.478	0.480	0.472
2	0.519	0.491	0.4	0.531	0.48	0.5110	0.48	0.486	0.511	0.491	0.492	0.485
3	0.524	0.495	0.518	0.535	0.522	0.4	0.492	0.4950	0.515	0.495	0.496	0.489
4	0.524	0.495	0.518	0.535	0.522	0.4	0.492	0.4950	0.515	0.495	0.496	0.489
5	0.526	0.497	50.5260	0.537	0.4	0.476	0.4970.4	0.492	0.517	0.497	0.498	0.491
6	0.519	0.491	0.4	0.531	0.48	0.5110	0.48	0.486	0.511	0.491	0.492	0.485
7	0.503	0.4	0.498	0.515	0.502	0.453	0.471	0.4740	0.495	0.4	0.476	0.468
8	0.395	0.369	0.394	0.410	0.397	0.347	0.3690.3	0.3690.3	0.389	0.369	0.369	0.360
9	0.387	0.361	0.36	0.402	0.389	0.338	0.355	0.354	0.361	0.361	0.361	0.352
10	0.354	0.329	0.354	0.370	0.357	0.306	0.32	0.32	0.348	0.329	0.329	0.318
11	0.395	0.369	0.394	0.410	0.397	0.347	0.3690.3	0.3690.3	0.389	0.369	0.369	0.360
12	0.412	0.386	0.4120	0.386	0.4120.3	0.3860.3	0.3850	0.379	0.405	0.385	0.386	0.377
13	0.428	0.402	0.426	0.402	0.393	0.379	0.396	0.396	0.422	0.401	0.402	0.393
14	0.428	0.402	0.426	0.402	0.393	0.379	0.396	0.396	0.422	0.401	0.402	0.393
15	0.453	0.426	0.4530	0.426	0.4530.4	0.4	0.421	0.4260	0.446	0.426	0.427	0.418
16	0.462	0.4	0.458	0.474	0.462	0.412	0.4340	0.429	0.4350.4	0.4	0.435	0.426
17	0.453	0.426	0.4530	0.426	0.4530.4	0.4	0.421	0.4260	0.446	0.426	0.427	0.418
18	0.449	0.422	0.446	0.422	0.450	0.4220	0.417	0.416	0.42	0.422	0.423	0.414
19	0.424	0.398	0.42	0.398	0.425	0.375	0.392	0.392	0.418	0.397	0.398	0.389
20	0.395	0.369	0.394	0.410	0.397	0.347	0.3690.3	0.3690.3	0.389	0.369	0.369	0.360
21	0.404	0.377	0.402	0.418	0.405	0.355	0.372	0.371	0.397	0.377	0.378	0.368
22	0.424	0.398	0.42	0.398	0.425	0.375	0.392	0.392	0.418	0.397	0.398	0.389
23	0.445	0.418	0.442	0.418	0.446	0.396	0.413	0.412	0.438	0.418	0.418	0.410
24	0.449	0.422	0.446	0.422	0.450	0.4220	0.417	0.416	0.42	0.422	0.423	0.414

Table 7
Parameters for the schematic model.

Parameter	Component	Default value
Fuel curve intercept coefficient	Fuel cell subsystem	0 $m^3/h/kW_{rated}$
Fuel curve slope	Fuel cell subsystem	0.21 $m^3/h/kW_{output}$
Heat recovery ratio	Fuel cell subsystem	60%
Lifetime (operating hour)	Fuel cell subsystem	40,000 h
Design hot water	Electric water heater	60 °C
Scaled annual average (electricity load)	Fuel cell subsystem	11 and 15
Scaled annual average (thermal load)	Fuel cell subsystem	3 and 5
Project lifetime	Whole system	20 years
Annual real interest rate	Whole system	5%

Table 8
Optimization variables.

Fuel cell (kW)	Converter (kW)	Battery (optional)
0.5	0.5	1
1	1	2
2	2	3
3	3	4
4	4	5
5	5	6

Table 9
Equipment price [5].

Equipment	Price
Fuel cell system	RM 3500/kW
O & M cost for fuel cell system	RM 300/year
Converter	RM 200/kW
Battery (optional)	RM 200
Thermal storage tank (optional)	RM 500

Table 10
Natural gas tariff for year 2008 [16].

Tariff category	Unit	Rates
The minimum monthly charge for the first 7 units	m^3	MYR 5.00
Subsequent units	m^3	MYR 0.75/m^3

In scenario A, where fuel cell system will operate for 8760 h a year and consumes about 916 m^3 of natural gas per year. This system will generate excessive electric and thermal energy over the demand required. Thermal storage tank is not required in this case as the thermal energy generated by the fuel cell system is enough to heat up the water to the desired temperature. The electricity production and consumption and the thermal energy generation and consumption for scenario A are tabulated in Tables 13 and 14 respectively.

Table 15.

4.3.2. Cogeneration system with battery—scenario B

The second scenario is using the battery option to store excessive electricity and this can minimize the operating hours of the fuel cell system. It can reduce the frequency of replacement of a new fuel cell system. Using the same data and parameters used in the previous evaluation, four sensitivities are simulated and each of them with 216 combinations. A system with a battery option with the total net present cost of MYR 18,978 is selected in this case. This optimal combination is called scenario B which also capable to meet the baseline demands which is 11 kWh/day for electricity load and 2 kWh/day for thermal load.

Battery suggested for this scenario is two units of Surrette 4KS25P from Rolls Battery manufacturer are used to optimize the usage of fuel cell. With the battery pack option, the lifespan of fuel cell is two times comparing to scenario A, which required four times throughout the lifespan of the project. This indirectly reduces the replacement cost as battery is only required to be

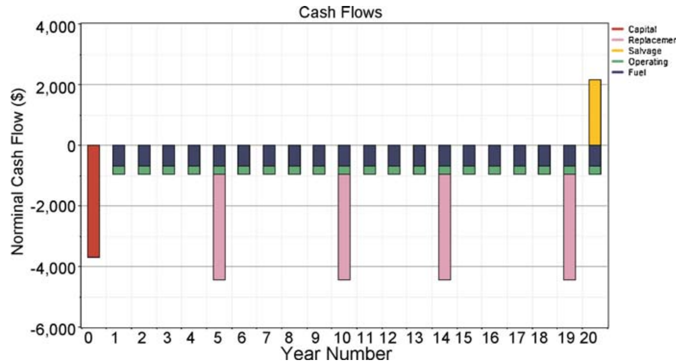

Fig. 10. Cash flows for scenario A.

Table 13
Electricity production and consumption for scenario A.

Fuel cell production (kWh/yr)	Primary load consumption (kWh/yr)
4364	4015

Table 14
Thermal energy generation and consumption for scenario A.

Thermal energy production (kWh/yr)	Thermal load consumption (kWh/yr)
2812	730

Table 11
Electricity tariff for year 2008 [17].

Tariff category	Unit	Rates
For monthly consumption between 0 and 400 kWh per month:		
For the first 200 kWh (1–200 kWh) per month	sen/kWh	21.8
For the next 200 kWh (201–400 kWh) per month	sen/kWh	34.5
The minimum monthly charge is RM3.00		
For monthly consumption more than 400 kWh per month:		
For the first 500 kWh (1–500 kWh) per month	sen/kWh	30.0
For the next 100 kWh (501–600 kWh) per month	sen/kWh	39.0
For the next 100 kWh (601–700 kWh) per month	sen/kWh	40.0
For the next 100 kWh (701–800 kWh) per month	sen/kWh	41.0
For the next 100 kWh (801–900 kWh) per month	sen/kWh	43.0
For the next kWh (901 kWh onwards) per month	sen/kWh	46.0
The minimum monthly charge is RM3.00		

Table 12
Net present cost (MYR) for scenario A.

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Fuel cell	3500	8272	3275	8566	−818	22,795
Converter	200	0	0	0	0	200
System	3700	8272	3275	8566	−818	22,995

Table 15
Net present cost (MYR) for scenario B.

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Fuel cell	3500	3954	1854	9501	−687	18,121
Surrette4KS25P	400	402	0	0	−144	657
Converter	200	0	0	0	0	200
System	4100	4356	1854	9501	−831	18,978

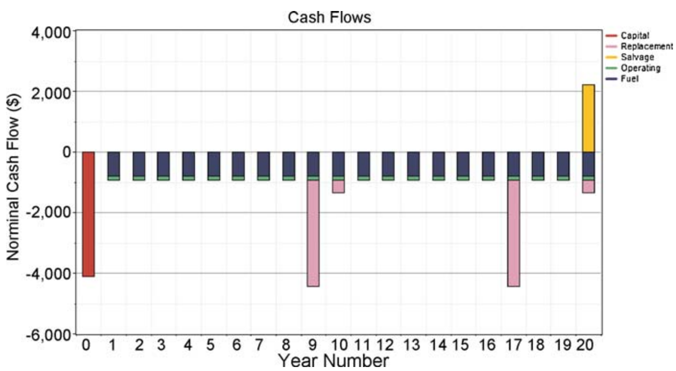

Fig. 11. Cash Flows for scenario B.

Table 16
Electricity production and consumption for scenario B.

Fuel cell production (kWh/yr)	Primary load consumption (kWh/yr)
4840	4015

Table 17
Thermal energy generation and consumption for scenario B.

Thermal energy production (kWh/yr)	Thermal Load Consumption (kWh/yr)
3118	730

replaced every 10 years. The salvage value for this case is MYR 831. Fig. 11, indicates the cash flow for scenario B.

For scenario B with the battery pack backup, fuel cell system only has to operate 4958 h to meet the required demands. The electricity production and consumption for scenario B is presented in Table 16.

Because the fuel cell system is not operating continuously; a thermal storage tank is needed in this case to store the excess of thermal energy. Table 17, indicates the thermal energy generated from the fuel cell system is more than required.

4.4. Life cycle cost analysis

The life cycle cost for the conventional residential energy systems and the fuel cell based cogeneration system are compared. The life cycle cost for all system includes the initial cost of the system, the energy cost and the maintenance cost are tabulated in Tables 18–20.

Table 18
Initial cost of all system (MYR).

Conventional Grid	Scenario A	Scenario B
390	3700	4100

Table 19
Total energy cost of all system (MYR).

Conventional Grid	Scenario A	Scenario B
15,063	8566	9501

Table 20
Total maintenance cost of all system (MYR).

Conventional grid	Scenario A	Scenario B
0	11,547	5808

For a new household in Malaysia, tenant/owner has to pay MYR 390 in order to obtain the electricity facilities and this assumed as the initial cost for conventional grid energy system.

With the electricity consumption data for the above typical household, the total energy cost or the fuel used is calculated based on the electricity and natural gas tariff (Tables 10 and 11). Table 19 shows that the new fuel cell system introduces a significant cost savings over the life time of the system. The energy cost savings of the cogeneration system compared to conventional system is range from 30% to 40%.

For the conventional grid system, the electricity company charge the maintenance cost on consumer. Therefore, the maintenance cost for the conventional systems is negligible compared to the life cycle cost of the systems. However, the maintenance cost for the fuel cell based energy system is high due to the fuel cell subsystem maintenance cost. This cost includes the expense of periodically of replacing the fuel cell subsystem.

The utility (gas and grid) connection and subscription cost are not included in the life cycle cost analysis as their variability. In general, the life cycle costs for the conventional system using only electricity from the grid and the fuel cell energy system uses only the natural gas from the pipeline to generate electricity and heat. A comparison of life cycle costs are calculated in accordance with equation (3) for the conventional and the fuel cell energy system is presented in Fig. 12. The main reason for this is fuel cell price is not compatible to the conventional system.

4.5. Payback period

The payback period used to determine the time taken for a capital cost of the project to recover its total cost. Based on Eq. (6), the payback period for Scenario A and Scenario B are approximately 34 years and 29 years respectively. Preference should be given to the shortest time of payback period which is

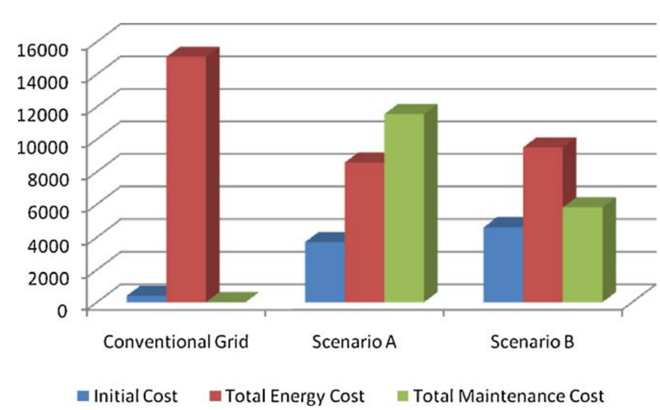

Fig. 12. Life cycle costs.

Scenario B. However, the lifetime of the system is 20 years, this means the above two situations is not viable to replace the conventional grid system with the current electricity, natural gas and fuel cell prices. However, there are limitations of the payback period which is it ignores any benefits that occur after the payback period, and it does not measure the time value of money.

5. Conclusions

The research on the fuel cell based cogeneration system indicates that it can become one of the alternative energy systems in the residential sector. However, it does not represent an attractive option to replace the conventional grid connected systems in Malaysia. Two schematic models are presented and evaluated with two different options. Scenario A without battery while Scenario B with the battery pack. From the above results, scenario B will be the optimal option. Design considerations for both scenarios based on 1 kW fuel cell subsystem. This conclusion is based on the 60% cogeneration efficiency of the system. While the thermal energy generated by the fuel cell subsystem is more than adequate. Both scenarios are not cost effective compared to conventional residential energy system although scenario B was the preference option based on the numerical model analysis results (net present cost, life cycle cost and the payback period). The life cycle cost analysis shows that the cogeneration system can compete with conventional residential energy systems, if the fuel cell subsystem costs can be reduced to MYR 2000/kW or lower.

References

[1] Energy Commissions. Electricity supply industry in Malaysia, performance and statistical information. Kuala Lumpur, Malaysia; 2006.
[2] Çengel YA, Boles MA. Thermodynamics: an engineering approach. 6/e McGraw-Hill; 2008.
[3] Daud WR. Hydrogen economy: perspective from Malaysia. National Fuel Cell Research Program Malaysia; 2006.
[4] Toyota. Toyota to continue providing residential fuel cell cogeneration system for government project. Toyota Motor Corporation; 2008.
[5] Gunes MB. Investigation of a fuel cell based total energy system for residential applications. Master thesis. Virginia Polytechnic Institute and State University; 2001.
[6] Taha FM. Development of energy labeling in Malaysia; past, present and future. Malaysia: Universiti Teknologi; 2000.
[7] Tang CK. Energy efficiency in residential sector. Malaysian—Danish Environmental Cooperation Programme Renewable Energy and Energy Efficiency Component; 2005.
[8] Choo SC. Techno-economical analysis of a residential photovoltaic vapour compression air conditioning system. Master thesis. Malaysia: Universiti Teknologi; 2005.
[9] Ugur S, Selamo G, Thomas R, David W, Torrey A. A systems approach for sizing a stand-alone residential PEMFC power system; 2007.
[10] Kadota A. Panasonic develops new fuel cell cogeneration system for home use. Matsushita Electric Industrial; 2008.
[11] Tanrioven M, Alam MS. Impact of load management on reliability assessment of grid independent PEM fuel cell power plants; 2005.
[12] Fuel cell handbook. U.S. Department of Energy. EG&G Technical Services, Inc. DE-AM26-99FT40575; 2004.
[13] National Renewable Energy Laboratory. Retrieved July 4, 2008, from http://www.nrel.gov; 2008
[14] ASHRAE. Service water heating. HVAC applications handbook. Publisher; 1999 [Chapter 48].
[15] NASA. Surface meteorology. Retrieved July 28, 2008, from http://eosweb.larc.nasa.gov; 2008.
[16] Gas Malaysia. Natural gas tariff. Kuala Lumpur, Malaysia; 2008.
[17] National Electricity Board. Electricity tariff. Kuala Lumpur, Malaysia; 2008.